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1/77

19NOV02 E764336-1 D10153
P01/7700 0.00-0226846.4

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The Patent Office
Cardiff Road
Newport
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NP10 8QQ

1. Your reference — P164-GB

2. Patent application number *(The Patent Office will fill in this part)* — 0226846.4 — 19 NOV 2002

3. Full name, address and postcode of the or of each applicant *(underline all surnames)* —
1... Limited
St John's Innovation Centre
Cowley Road
Cambridge CB4 0WS

Patents ADP number *(if you know it)* — 8113870001

If the applicant is a corporate body, give the country/state of its incorporation — England

4. Title of the invention — CURVED ELECTRO-ACTIVE ACTUATORS WITH INTEGRAL TERMINALS

5. Name of your agent *(if you have one)* — Akram K. Mirza

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)* —
1... Limited
St John's Innovation Centre
Cowley Road
Cambridge CB4 0WS

Patents ADP number *(if you know it)* — 8243347001

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
a) any applicant named in part 3 is not an inventor, or
b) there is an inventor who is not named as an applicant, or
c) any named applicant is a corporate body.
See note (d)) — YES

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Patents Form 1/77

9. Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document

Continuation sheets of this form	0
Description	9
Claim *(s)*	2
Abstract	
Drawing *(s)*	6 only

10. If you are also filing any of the following, state how many against each item.

Priority documents

Translations of priority documents

Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*

Request for preliminary examination and search *(Patents Form 9/77)*

Request for substantive examination *(Patents Form 10/77)*

Any other documents *(please specify)*

11. I/We request the grant of a patent on the basis of this application.

Signature

Date 19-NOV-2002

12. Name and daytime telephone number of person to contact in the United Kingdom Akram K. Mirza 01223-422290

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Notes

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b) *Write your answers in capital letters using black ink or you may type them.*

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P164-GB

CURVED ELECTRO-ACTIVE ACTUATORS WITH INTEGRAL TERMINALS

FIELD OF THE INVENTION

This invention relates to curved elements of electro-active material. More particularly, the invention related to electro-active actuators having integral terminals for mechanical and/or electrical connection to a supporting structure or object to be displaced or forced.

BACKGROUND OF THE INVENTION

Electro-active materials are materials that deform or change their dimensions in response to applied electrical conditions or, *vice versa*, have electrical properties that change in response to applied mechanical forces. The best-known and most used type of electro-active material is piezoelectric material, but other types of electro-active material include electrostrictive and piezoresistive material.

Many devices that make use of electro-active materials are known. The simplest piezoelectric device is a block of pre-poled, i.e., pre-oriented, piezoelectric material activated in an expansion-contraction mode by applying an activation voltage in direction of the poling.

Because piezoelectric devices are capacitive in nature, they exhibit a number of desirable mechanical and electrical characteristics. They have a very efficient coupling of energy from applied charge to mechanical strain, leading to a high bandwidth, a large force output and negligible resistive heating. Due to their capacitive nature, these devices draw their least current at zero rate of displacement. The electro-active material, which in general is crystalline, ceramic or polymer-based, determines the stiffness of electro-active devices. However, as the electro-active effects are extremely

small, e.g. in the order of 1 nm/V, the change in dimensions is relatively small and requires high voltages. Therefore, more complicated electro-active structures have been developed to achieve larger displacements.

To increase the displacements, several designs have been introduced such as stacks, unimorph or bimorph benders, recurved benders, corrugated benders, spiral or helical designs.

Benders, stacks, tubes and other electro-active actuators are employed in a wide array of engineering systems, ranging from micro-positioning applications and acoustic wave processing to printing applications. Generally, actuators are used in such applications to generate force and effect displacement, for example, to move levers or other force transmitting devices, pistons or diaphragms, to accurately position components, or to enable similar system functions. Actuators employed for such functions are typically designed to provide a desired displacement or stroke over which a desired force is delivered to a given load.

Depending upon design, electro-active actuators can generate a rotational or translational displacements or combinations of both movements.

Comparably large translation displacements have been recently achieved by using a helical structure of coiled piezoelectric tape. Such twice-coiled or "super-helical" devices are found to easily exhibit displacement in the order of millimetres on an active length of the order of centimetres. These structures and variations thereof are described, for example, in the published international patent application WO-0147041 or by D.

H. Pearce et al in : Sensors and Actuators A 100 (2002), 281 - 286.

These structures are ceramic devices of complex curved shape. The brittleness of the material makes handling and mounting such actuators a slow and delicate task

For many applications, it becomes necessary to connect and attach these actuators in such a way that the mechanical and electrical connections to the actuator are robust and capable of creating strain within the actuator or displacing or forcing the system, and to couple this strain, motion or force to the object which is to be controlled.

In a typical application, a piezoelectric element is bonded to a structure in a complex sequence of steps. The surface of the structure is first machined so that one or more channels are created to carry electrical leads needed to connect to the piezoelectric element. Alternatively, instead of machining channels, two different epoxies may be used to make both the mechanical and the electrical contacts. In this alternative approach, a conductive epoxy is spotted, i.e., applied locally to form conductors, and a structural epoxy is applied to the rest of the structure, bonding the piezoelectric element to the structure. The whole structure may then be covered with a protective coating.

During all of these steps there is a risk of damaging and breaking the electro-active structure. This problem is addressed in many published documents relating to the connection of piezoelectric devices to board, substrates and the like, including the United States patent nos. 2,877,363; 4,240,002; 4,404,489; 5,404,067; 5,622,748 and 6,420,819.

However, none of the known solutions related to curved electro-active devices, particularly complex shaped devices such as the twice-coiled or super-helical actuators referred to above.

It is therefore seen as an object of the present invention to provide improved complex curved electro-active structures that are easier to handle in post-firing, mounting and packaging operations are easier to manufacture.

SUMMARY OF THE INVENTION

In view of the above objects, the present invention provides apparatus and methods as claimed in the independent claims.

According to a first aspect of the invention, there is provided a permanently curved actuator of electro-active material with at least one essentially flat projecting tab portion, wherein a curved end of said actuator extends into said tab.

In a preferred embodiment the curved actuator includes portions that are helically wound benders. At the end of such helically wound portions the actuator has a nominally circular cross-section with the axis of the helix as center. The projecting tab projects preferably tangentially to that circle, however in other embodiments the tab may bend to form an angle with a tangent to the circle. Alternatively, the projecting tab may be formed to project into a direction parallel to the axis of the helix.

In a particularly preferred embodiment the axis of the helical portions of the actuator are curved to form a twice coiled or super-helical actuator.

The length of the flat portion is preferably equal or larger that the outer diameter of the curved actuator. Where the curvature changes, a nominal outer diameter can be defined by using the radius of curvature in the curved portion from which the flat terminal projects.

In another preferred embodiment the projecting tab provides contact terminals for the electrodes of the piezoelectric actuator. Most preferably electrical contacts can be made to operating electrodes, i.e., electrodes used during the activation of the device but not necessarily during poling, from a single exposed surface of the tab. For this purpose, electrically conductive layers are either wrapped around part of the tab or, alternatively, the tab includes openings or covered electrodes.

These and other aspects of inventions will be apparent from the following detailed description of non-limitative examples making reference to the following drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1A is a perspective view on a twice-coiled actuator with a terminal in accordance with an example of the present invention;

FIG. 1B is a perspective view on a twice-coiled actuator with a terminal in accordance with another example of the present invention;

FIG. 1C is a perspective view on a twice-coiled actuator with a terminal in accordance with another example of the present invention;

FIG. 1D is a perspective view on a twice-coiled actuator with a terminal in accordance with another example of the present invention;

FIG. 2 shows a schematic cross-section illustrating a possible electrical connection arrangement; and

FIG. 3 is a perspective view of a twice-coiled actuator with terminal tab on a circuit board;

DETAILED DESCRIPTION

Three different configurations of a curved actuator with a projecting tab are shown in FIGs. 1A-D.

The actuator **11** is a of twice coiled or super-helix actuator of the type described in the above-mentioned WO-0147041 and Sensors and Actuators A 100 (2002), 281 -286.

The actuator has a curved portion **12** of bimorph tape that is wound helically. The helically wound portion is further coiled into a secondary winding of about two-thirds of a complete turn. The first winding is known as the primary winding or primary helix. The secondary winding could exceed one turn and form a spiral or secondary helix. It is therefore usually referred to as secondary helix.

Whilst this actuator is known per se, the present invention facilitates the mounting and contacting of the actuator for

industrial production. In the known configurations of this type of complex-shaped actuator, soldering thin wires to the two outer electrodes and the inner electrode of the bimorph tape has provided electrical contacts.

Apart from being cumbersome and error prone, this known methods do not lend itself readily for mass manufacturing as the soldering operations have to be performed with high accuracy to prevent short circuits and loss of contact.

The new configurations in accordance with the present invention propose to extend the first winding or turn **121** (and/or the last winding **122**) of the primary helix to be extended into an essentially flat terminal portion **13**.

The direction into which the terminal portion **13** extends may vary. In FIG.1A the terminal portion **13** extends essentially tangentially from the first winding **121**. To allow a flat mounting on a board, the pitch angle of the terminal portion **13** is essentially equal or less than the pitch angle of the secondary helix. Where, as shown, the pitch angle is zero the terminal tab **13** and the secondary helix are co-planar.

In FIG. 1B the projecting tab **13** again extends tangentially from the first winding **121**. It is oriented essentially perpendicular to the plane of the secondary helix or arranged at 90 degrees plus the pitch angle to the plane of the secondary helix.

In FIG. 1C, the projecting terminal **13**, initially oriented tangentially, includes a bend portion **131** that provides an arbitrary orientation to the remaining portion of the terminal **13**.

In FIG. 1D, the projecting terminal **13** is edge bent to extend essentially in a direction parallel to the axis of primary helix.

In FIG. 2 a cross-section of the terminal tab **23** is shown. The hatched portions are electrically conductive and comprise the electrodes **211**, **212**, **213** required to pole and activate the actuator. The terminal also has two isolated pads **232**, **233** at one surface. Electrically conductive paths **134**, **135** within openings punched or drilled through the terminal connect these pads to the inner electrodes **112** and the second outer electrode **213**. As a result all electrodes **211**, **212**, **213** of the actuator can be contacted from a single face **236** of the terminal **23**.

A difficulty to be overcome when producing curved ceramic structures with projecting tabs lies in the plasticity of the green tape used as an intermediate in the manufacturing process of complex ceramic actuators.

To fabricate the actuators of FIGs. 1A-D, a commercial piezoelectric lead zirconate titanate (PZT) powder can be used as the strating material, for example TRS 600 (TRS Ceramics Penn., USA. The powder is mixed with polyvinyl butyral binder and cyclohexanone on a twin-roll mill until a uniform 1 mm thick sheet is obtained. This material is then rolled up and extruded to obtain a uniformly thick and defect-free sheet. The sheet is then calendered to the required thickness being half of that of the final bimorph tape. The bimorph structure is produced by screen printing the tape with conductive ink such as platinum ink. Two or more of these tapes can then be laminated to form bimorphs. Strips of suitable width are cut from the tape and wound on to a first cylindrical former the outer diameter of which determines the inner diameter of the

primary helix. The strips are then placed into a second former that determines the secondary helix radius.

The second former has a shallow groove or a narrow cut into which the end of the laminated strip is placed. The dimensions and orientation of the shallow groove or a narrow cut, together with the length of the ceramic strip placed into it determine the orientation and length of the final terminal tab.

The assembled structure is then dried to remove solvents and plastizers. At this stage support for the projecting terminal may not be necessary as the structure becomes sufficiently rigid to not collapse under its own weight. The actuator is then fired. Following a slow binder removal stage up to 600 degrees C, the material is sintered at 1200 degrees C for 1 hour.

Soldered electrode contacts were made to the outer two electrodes and the single inner electrode. The material was poled in a heated silicone oil bath at 120 degrees C and 2.5kVmm-1 for 10 minutes. After cleaning, the outer two electrodes were joined together to form a single external electrode and the central electrode used to generate the required opposing actuation fields.

An example of a packaged actuator manufactured in accordance with the above steps is shown in FIG. 3. The curved actuator 31 is mounted over an opening of a board 32 suspended only at the projecting tab or terminal 33. The tab is connected to the board at several soldering points 34. The assembled structure can be mounted onto larger structures, such as a PCB board, via three connection pins 35.

CLAIMS

1. An electro-active actuator comprising a permanently curved portion of electro-active material and at least one essentially flat projecting tab portion adapted as terminal for electrical connections, wherein said permanently curved portion extends into said tab.

2. The electro-active actuator of claim 1 wherein the permanently curved portion forms a helix or spiral.

3. The electro-active actuator of claim 1 wherein the permanently curved portion forms a primary helix with said primary helix bend into a secondary helix..

4. The electro-active actuator of claim 1, 2 or 3 wherein the projecting tab extends tangentially from the permanently curved portion.

5. The electro-active actuator of any of the preceding claims wherein the projecting tab has a length equal or exceeding an outer diameter of the curved portion.

6. The electro-active actuator of any of the preceding claims wherein the projecting tab comprises all contact points for electrical connections between the actuator and an exterior power supply.

7. The electro-active actuator of claim 6 wherein the contact points are located on one face of the tab.

9. The electro-active actuator of claim 1 wherein the electro-active material is a ceramic material.

10. A method of manufacturing an electro-active actuator having a permanently curved portion of electro-active material and at least one essentially flat projecting tab portion adapted as terminal for electrical connections, wherein said permanently curved portion extends into said tab comprising the steps of
- preparing a ceramic tape in a green state;
- placing said tape into a former having a section to support said tab and maintain the orientation of said tab with respect to the permanently curved portion of the actuator; and
- drying said tape within said former to reduce the plasticity of said tape.

11. An actuator constructed and arranged to operate substantially as hereinbefore described hereinbefore with reference to the accompanying drawings.

ABSTRACT

Curved electro-active actuators and methods of manufacturing such actuators are described having a flat terminal tab projecting from a permanently curved potion of the actuator.

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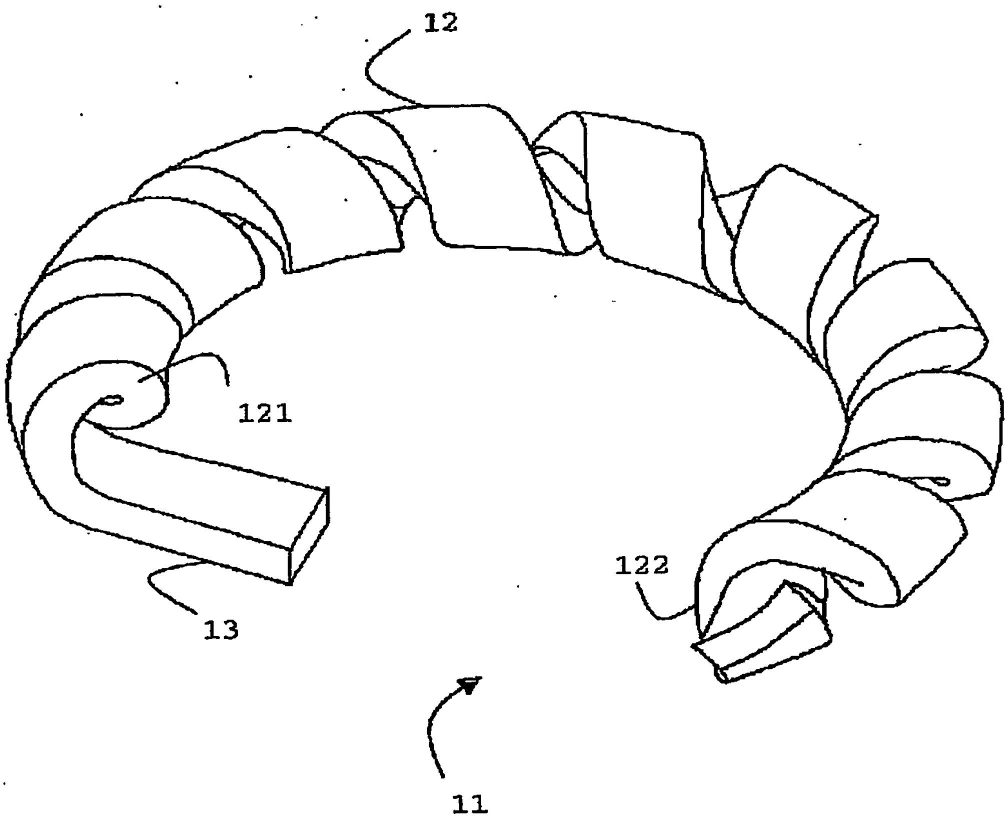

FIG. 1A

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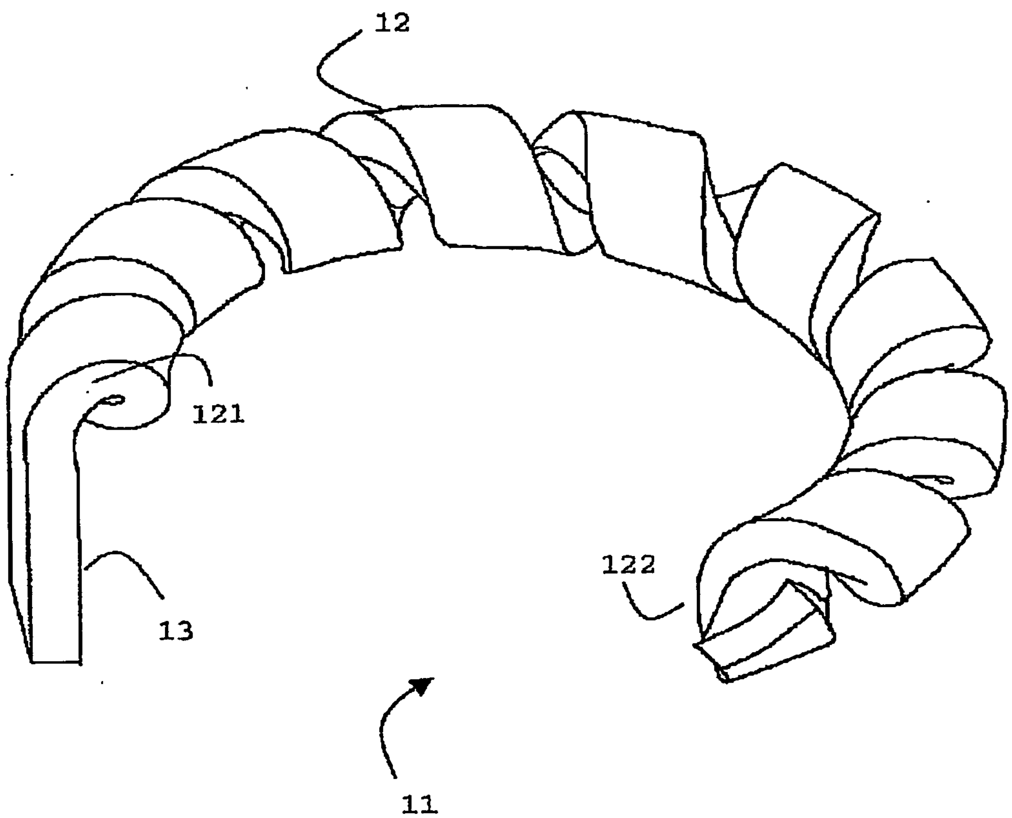

FIG. 1B

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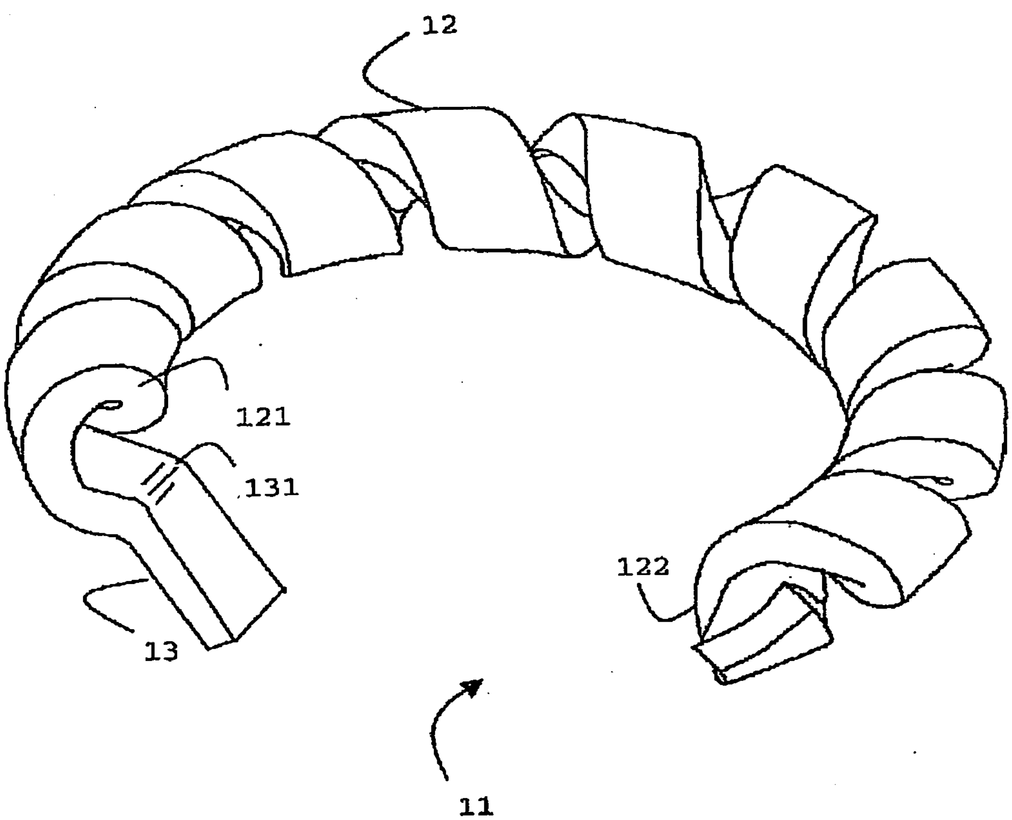

FIG. 1C

164-GB

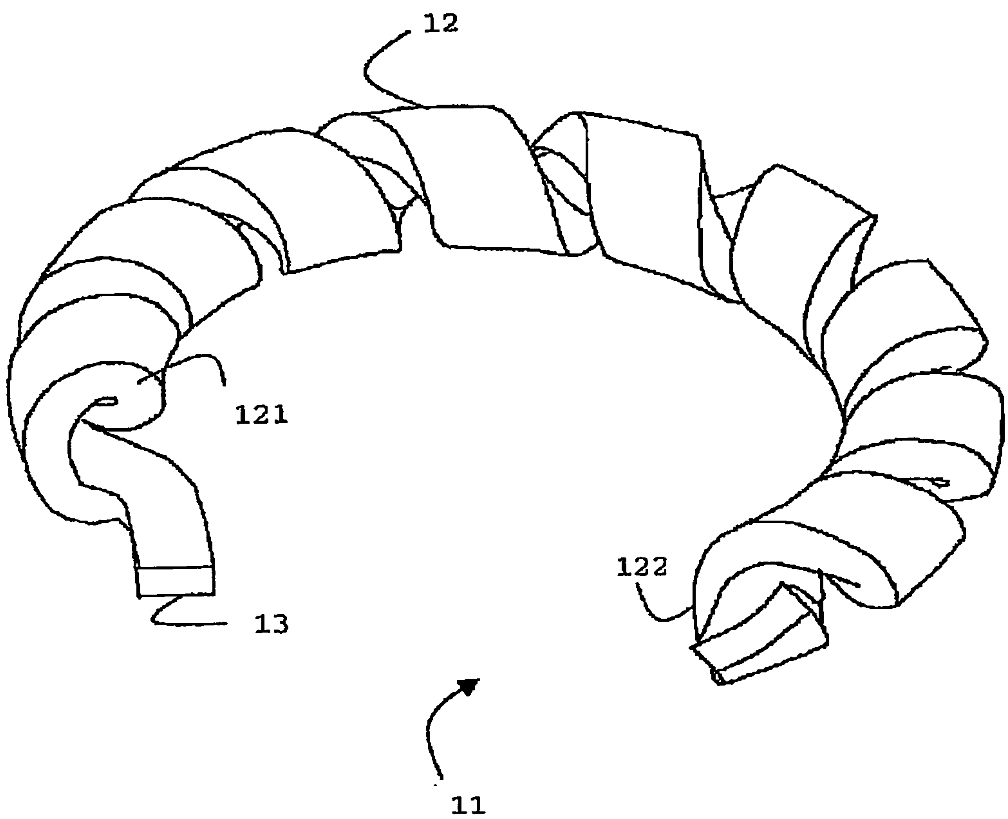

FIG. 1D

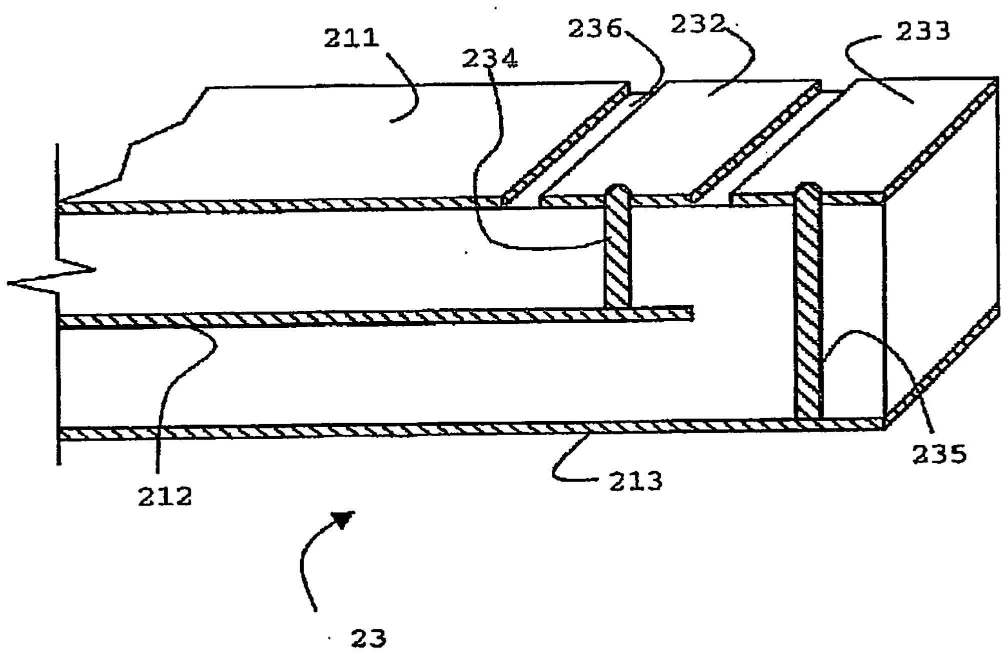

FIG. 2

64-GB

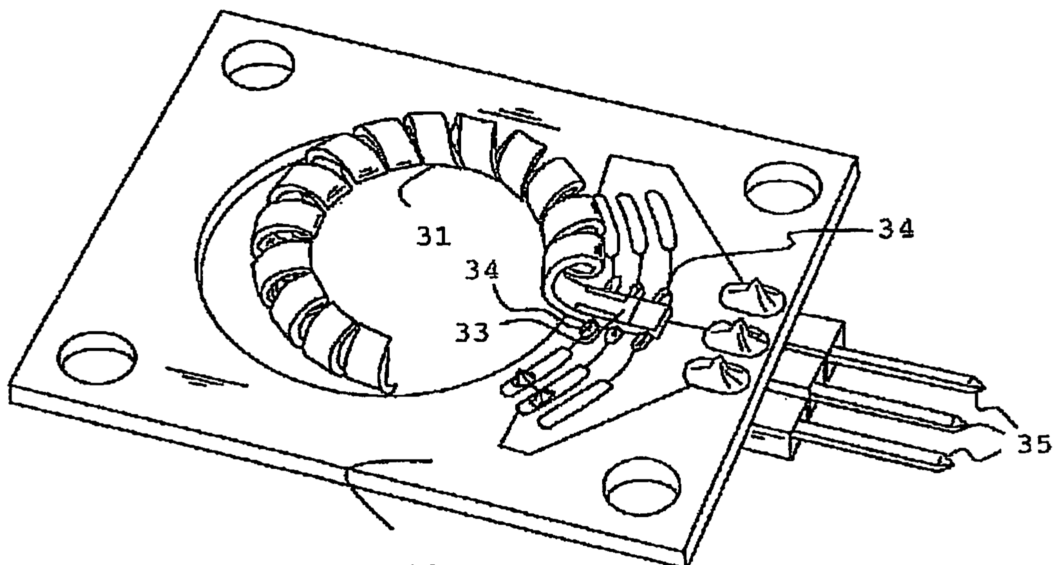

FIG. 3